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The influence of unsealing on the wind resistance of asphalt shingles

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ABSTRACT

This paper addresses the wind-induced tearing and blow-off of asphalt roofing shingles, which are the most frequently observed forms of residential building damage in hurricanes. Field surveys indicate that in-service asphalt shingle sealant strips can lose adhesion along their leading edge over time, leaving the shingle partially unsealed and susceptible to wind uplift. Two interrelated studies presented in this paper show that unsealing is a naturally occurring process and that unsealed shingles are a contributing cause of shingle roof cover damage in high winds. The first study quantified the number, location, and failure mode of laminate and three-tab style shingle systems installed on residential buildings at 30 sites in Florida and Texas. Systematic patterns of partially unsealed field shingles found on 22 of the 30 roofs resembled spatial patterns of wind-induced shingle damage observed in post-hurricane building performance assessments. As expected, older roofs generally contained more unsealed shingles than newer roofs. The results of the second study link blow-off to partially unsealed shingles. Seventeen ASTM D7158 Class H asphalt shingle roofs were aged outside for nominally one year at the Insurance Institute for Business & Home Safety Research Center and then evaluated in full-scale wind tunnel tests. Partially unsealed field and hip shingles frequently exhibited damage during wind testing, while fully sealed shingles were not damaged unless adjacent, unsealed shingles failed first.

1. Introduction

Asphalt shingles are the most popular roof covering system in the U.S. residential construction market (ARMA, 2011) due to their relatively low installation cost and range of aesthetic options (Noone and Blanchard, 1993). A shingle system consists of overlapping strips of asphalt impregnated organic or glass fiber mats that function as a water shedding skin for structural roof decking. Asphalt shingles manufactured after the 1950s usually have an adhesive asphalt-based sealant strip embedded on the top or lower surface of the shingle that adheres when the roof temperature exceeds the sealant's softening point. It restrains the edge from rising under wind load and transfers surface wind pressure to the shingle course below (Peterka et al., 1997). Understanding the mechanism causing unsealing and its role in wind-induced damage are critical to reducing losses in windstorms. Applied Research Associates (2008) analyzed residential building insurance claims from Hurricanes Charley, Frances, Ivan, and Wilma and determined that roof covering damage caused half of the insured losses.

This paper shows that damages are most likely attributed to shingle sealant strips losing adhesion along their leading edge over time, leaving the shingle partially unsealed and susceptible to wind uplift. Although this study addresses the performance of asphalt shingles in hurricane-prone regions, the findings are extensible to other areas in North America that experience extratropical and winter storms. They can supplement the knowledge base for products intended for cold climates (e.g., Fronapfel, 2006). These regions follow the same or similar performance requirements as hurricane-prone regions (e.g., ASTM D7158 and ASTM D3161); though, adhesive sealant strip formulation can vary between hotter and colder climates.

2. Background

Dixon et al. (2012) presents a detailed history of asphalt shingle design for high wind areas, beginning from its introduction of shingles in the late 1900s to the development of modern standards. This paper focuses on the role of the sealant strip in damage

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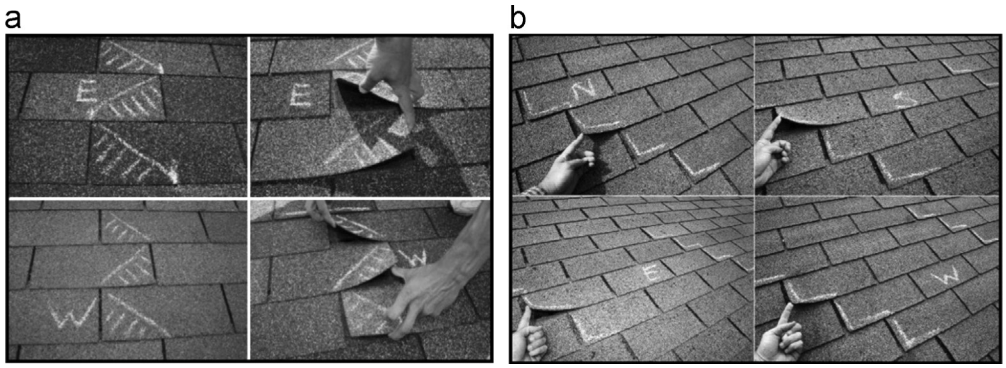

Fig. 1. Patterns of partially unsealed asphalt shingles reported in Marshall et al. (2010). (© American Meteorological Society. Used with permission).

caused by hurricanes (FEMA, 2005a, 2005b, 2006, 2009; Gurley and Masters, 2011; Liu et al., 2010; Rickborn, 1992; RICOWI, 2006, 2007; Smith, 1995, 1996; Smith and McDonald, 1990). Loss of adhesion causes the shingle to lift in strong winds, which creates additional uplift force from positive pressure on the shingle's bottom surface (Peterka et al., 1997) and transfers the load path to the fasteners at the upslope end of the shingle.

Little is known about unsealing of shingles. The current design approach assumes that shingles remain fully adhered throughout their service life. Performance test standards that establish wind ratings of shingles (e.g., ASTM D3161 and ASTM D7158) evaluate new, fully sealed specimens and do not account for long-term changes arising from weathering and aging of the material.

Marshall et al. (2010) first addressed the systematic loss of adhesion of in-service sealant strips, finding that unsealing occurs where shingles span the offset end joint of the shingle row (i.e., course) below (Fig. 1). Three-tab shingles are installed with an offset of one-half tab width between courses, thus one-half of the tab width is unsealed and the remaining half is sealed. The study attributed the long-term expansion and contraction in the shingle system arising from diurnal temperature cycles as the causes of unsealing. However, the sample size and a lack of data on roof ages, failure modes of the sealant strips, and exposure to windstorms precluded determining if unsealing is linked to wind damage.

This paper builds upon these findings and expands the knowledge base on the performance of in-service shingles, their vulnerability in wind, and the extent of impact unsealing has on shingle roof damage. The first of two studies presented describes a field assessment of 30 single-family homes in Florida and Texas to characterize the occurrence of unsealed shingles on field, hip, and ridge roof regions. Shingles appear to remain sealed for the first 4–5 years of service life, but beyond that timeframe, the frequency of unsealing trends upward. These findings are consistent with post-hurricane assessments by Gurley and Masters (2011) and Liu et al. (2010), which found that shingle roofs with six or more years of weathering were damaged at a 50% higher rate than newer shingle roofs. In the second study, 17 asphalt shingle roof systems were subjected to full-scale wind testing at the Insurance Institute for Business & Home Safety (IBHS) Research Center. The findings indicate that unsealing of shingles is a likely contributor to shingle roof cover damage reported in post-hurricane assessments.

3. Study 1: Survey of naturally aged shingle roofs for unsealed shingles

This research assessed the adhesion of the shingle sealant strips on in-service roofs on single-family homes in Florida and Texas. In 2012, a total of 27 roofs were surveyed in Altamonte Springs (two roofs), Gainesville (three roofs), Volusia County (four roofs), and Sarasota (18 roofs). Fig. 2 depicts the locations. Roof slopes ranged from 4 units vertical by 12 units horizontal (4:12) to 7:12. Ten roofs were three-tab style, and 17 were laminate style. For the Florida surveys, over 6100 m^2 (66130 ft^2) of shingle roofing was surveyed, corresponding to a sample size of 46,800 shingles. The installation age for 23 of 27 Florida roofs was obtained from the homeowner or roofing permit records. The shingle age was defined as the time from the installation to the survey. The age distribution was: 0–6 years (six roofs), 7–13 years (ten roofs), 14–20 years (seven roofs), and unknown (four roofs). Access to these roofs was made possible through a Florida Department of Emergency Management grant or personal contact with the homeowner.

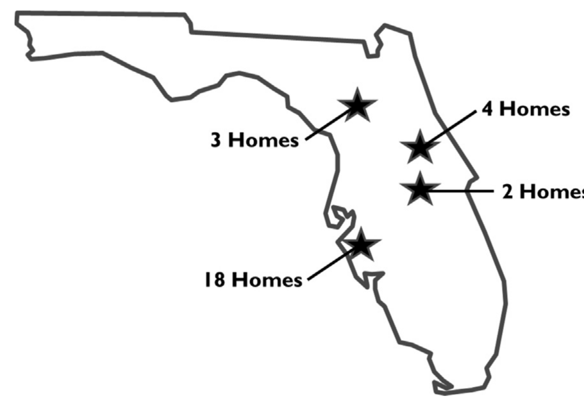

Fig. 2. Locations of the asphalt shingle surveys conducted in Florida.

Insight Engineering and Cross-Pointe Construction provided information about three additional shingle roof systems in the Houston, Texas metropolitan area that were surveyed in February 2013. The roof covers were installed within approximately 4.5 years prior to the survey as part of repairs resulting from Hurricane Ike (2008). One roof consisted of three-tab shingles and two roofs consisted of laminate shingles.

3.1. Survey method

Individual shingles were manually inspected (Fig. 3). Survey personnel gently applied upward pressure by hand to the leading edge. Each shingle was classified as: (1) sealed, (2) partially unsealed, or (3) fully unsealed. A sealed shingle was defined as a shingle with either full adhesion of the sealant strip or lack of adhesion over a continuous length of less than 51 mm (2 in.). A partially unsealed shingle was defined as any loss of adhesion on the shingle that was greater than or equal to a continuous 51 mm (2 in.) length, whereas a fully unsealed shingle was defined as the loss of adhesion along the entire length of the sealant strip. Strips of colored tape or chalk marks were placed on the top surface of each partially or fully unsealed shingle to aid in the identification of patterns. Post-survey, the following data were recorded on a roof plan:

1. Location on the roof
2. Unsealed location on the strip (e.g., left corner, center, right corner)
3. Unsealed length
4. Plane within the shingle composite where the loss of adhesion occurred to determine the sealant strip failure mode (cf. Shiao et al., 2003)

3.2. *Potential for wind induced loss of shingle sealing*

Extreme wind climatology in Florida and along the Texas coast is predominantly associated with hurricanes, thus the peak wind speeds at each survey were extracted from H*Wind swath datasets (cf. Powell et al., 1998) to assess historical wind events as a potential cause of partially unsealed shingles (Table 1). Wind speed estimates were obtained for all tropical cyclones from 1992 to the date of roof survey, which encompasses all but four roof lifespans in the study. H*Wind swaths are reported as maximum 60 s wind speeds (V_{60}) in open exposure at 10 m (33 ft) for all land areas. Following the approach of Masters et al. (2010), H*Wind velocities (i.e. the 60 s mean wind speed at 10 m in open country) were converted to mean wind speeds at 5 m (16 ft) in suburban exposure (to maintain consistency with the sites), which nominally corresponds to the mean eave height of a single story home in suburban terrain ($z_0=0.3$ m). The conversion factor was 0.48. Next, the factor was multiplied by a speed-up factor of 1.8 to convert the mean wind speed to the peak instantaneous velocity expected to occur on the roof deck (Dixon et al., 2013). Thus the total conversion factor was 0.87.

Altamonte Springs experienced the highest near-roof gust of all locations, 25 m/s (56 mph), during Hurricane Jeanne (2004). The second highest near-roof gust occurred in Ormond Beach during Hurricanes Floyd (1999) and Irene (1999), 22 m/s (49 mph). The remaining sites experienced near-roof gust wind speeds ranging from 11 to 21 m/s (25–47 mph). All of the wind speed estimates are lower than the 27 m/s (60 mph) maximum near-roof velocity threshold used in the ASTM D3161 fan test for shingle wind resistance certification, which is the lowest threshold used by product approval standards in the last two decades.

Based on these assessments, it was concluded that it is unlikely an extreme wind event caused the unsealing, acknowledging that absent a long-term monitoring program, it is not possible to prove if wind loads induced at lower wind speeds cause the unsealing. However, the systematic nature of the partially unsealed shingles detailed in the next section and the lack of observed surface cracking and tearing normally associated with shingle wind damage (FEMA, 2005a, 2005b, 2009; RICOWI, 2006, 2007) support the assertion that wind was not the cause of the shingle tabs losing adhesion.

3.3. *Survey results*

3.3.1. *Shingles in the field of the roof*

More than 99% of the unsealed shingles found on the Florida roofs exhibited the patterns of unsealing reported in Marshall et al. (2010). Partially unsealed shingles were found on eight of 10

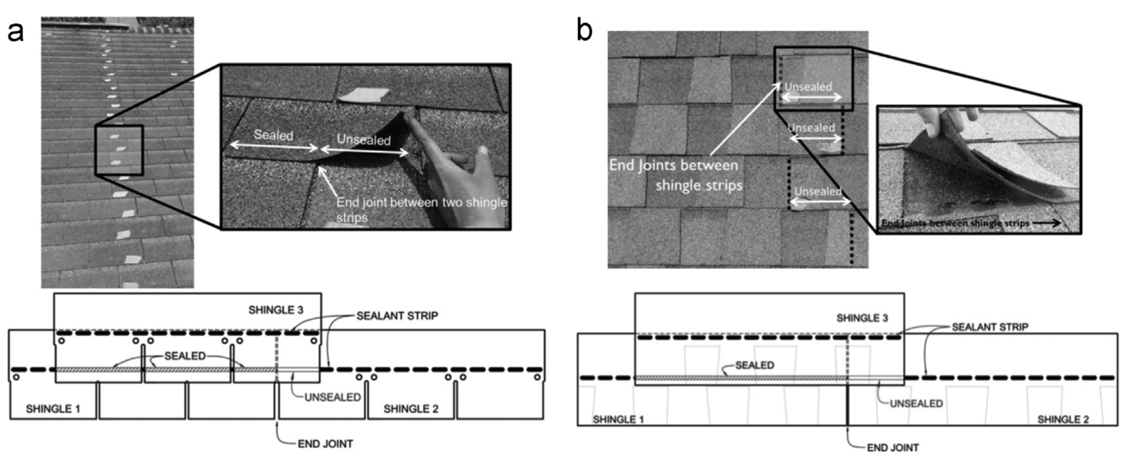

Fig. 3. Location of partial unsealing for (a) three-tab and (b) laminate shingle systems.

Table 1
Estimates of peak instantaneous velocity near the roof plane at each survey location.

Survey location	Analyzed hurricane seasons	Peak wind speed above the roof plane (m/s) [mph]	Tropical cyclone name (year)
Altamonte Springs, FL	2002–2011[a]	25 [56]	Jeanne (2004)
Gainesville, FL	1992–2011[b]	11 [25]	Frances (2004)
Orange City, FL	2002–2011[a]	21 [47]	Jeanne (2004)
Ormond Beach, FL	1992–2011[b]	22 [49]	Floyd (1999) and Irene (1999)
Sarasota, FL	1992–2011[b]	18 [40]	Frances (2004)
Houston, TX	2009–2012[c]	None reported	No tropical cyclones

[a] No roofs installed prior to 2002.
[b] Location contains roof(s) with unknown installation date.
[c] No roofs installed prior to 2009.

Fig. 4. Tape on roof denotes the location of partially/fully unsealed three-tab and laminate shingles. The pattern of successive courses with unsealed shingles corresponds to the direction of shingle installation (e.g., vertically or diagonally).

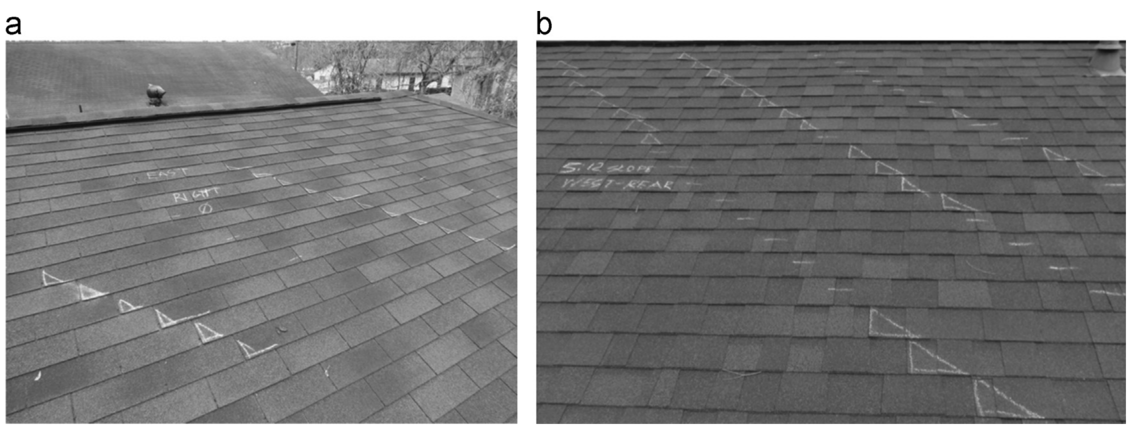

Fig. 5. (a) Three-tab and (b) laminate shingle roofs located in Houston, TX with partially unsealed shingles located by triangular chalk marks and fully sealed shingles located by dash marks.

three-tab shingle roofs and 11 of 17 laminate shingle roofs for a total of 19 of 27 surveyed roofs (70%). The partial unsealing of three-tab shingles typically occurred on the outside end tab of the strip where the end joint of the shingle course below, aligned with the centerline of the tab (Fig. 3a). Laminate shingles exhibited a similar pattern of unsealing to the three-tabs with the unsealed length running from the end joint of the strip to the end joint of the shingle course below (Fig. 3b). The unsealed length for laminate shingles appears to be controlled by the horizontal offset selected by the installer—typically 102 mm (4 in.) to 178 mm (7 in.). As shown in Fig. 4, the resulting alignment of partially unsealed shingle locations produced easily observable patterns that were installation specific, i.e., vertically aligned for vertical (racked) installations and diagonally aligned for diagonal installations.

Cohesive failure in the sealant was dominant. Adhesive residue of the unsealed portion of the sealant strip was visible on both the bottom surface of the top shingle and top surface of the bottom shingle, which indicates that the shingles were initially fully sealed. Fully-driven nails were found in the sealant strip on some partially unsealed shingles; however this was determined not to be a controlling factor because there was consistency in failure mode and unsealed length for shingles with and without fully-driven nails in the sealant strip.

All surveyed roofs in the Houston, TX metropolitan area contained partially unsealed field shingles exhibiting the same location of unsealing and sealant strip failure mode as the Florida roof surveys and in Marshall et al. (2010). Fig. 5 shows an example of the survey results on a portion of the three-tab roof and one laminate roof. The triangular marks represent the location and length of unsealing on the shingle and dash marks represent shingle strips or tabs that are fully sealed. Similar to the Florida roof surveys, the patterns of partially unsealed shingles in Texas corresponded to the direction of field shingle installation.

Fig. 6 shows the percentage of unsealed shingle strips on each roof as a function of roof age. The black square markers correspond to roofs with patterns of partially unsealed shingles that exhibited patterns found in Marshall et al. (2010). The gray circle markers depict roof coverings without partially unsealed shingles. Roofs containing the type of partially unsealed shingles described above had a range of less than 1% up to 86% of their shingle strips unsealed. The age of the roof with 86% unsealed strips was unknown and, therefore, not shown in Fig. 6. All roofs containing unsealed strips with no discernible pattern had less than 1% of their shingle strips unsealed. Fig. 6 also shows that the percentage of unsealed shingles for all roofs less than six years old is less than 1%, while 14 of 17 roofs older than six years had more than 1% of their shingles partially or fully unsealed.

Fig. 7 shows a box plot of the percentage of unsealed shingles as a function of each age group. Roofs were stratified into three age ranges with the following distribution: 0–6 years (six roofs), 7–13 years (10 roofs), and 14–20 years (seven roofs). The inset shows the result of a single-sided Welch's *t* test (Ott and Longnecker, 2004) comparing the mean values among the three groups. A statistically significant increase in the mean percentage of unsealed shingles was established at a 95% confidence level when the 0–6 age range was compared with the 7–13 age range (p-value$=0.02$) and 14–20 age range (p-value$=0.02$). A statistically significant increase was established between the 7–13 and 14–20 age ranges at a 90% confidence level (p-value$=0.08$).

In summary, the roof surveys conducted in this study and reported in Marshall et al. (2010) demonstrate: (a) partially unsealed shingles in the field of the roof exist in hurricane-prone Florida and Texas, (b) the nature of the unsealing is systematic and not induced by wind, and (c) the loss of adhesion increases with roof cover age. A relationship between likelihood of wind damage and the pre-wind presence of unsealed shingles can be drawn when the findings of the roof surveys are combined with the Liu et al. (2010) study which showed a 50% increase in wind damage frequency on shingle roofs greater than six years old. Furthermore, photos of damaged shingle roofs reported in post-hurricane damage investigations reveal blow off patterns (Fig. 8) that are strikingly similar to the patterns of partially unsealed shingles observed both in this study (Figs. 4 and 5) and Marshall et al. (2010) (Fig. 1). The damage pattern photographs in Fig. 8 were chosen from many that are similar in the nature of the damage pattern. There is no information to indicate whether the damaged shingles in Fig. 8 were unsealed prior to the wind event. However, the shingle tabs blown off from Hurricane Ike in Fig. 8b were located above the end joint of the shingle course below, identical to the observed location of partially unsealed shingles found in the roofs surveyed in this study (Fig. 3).

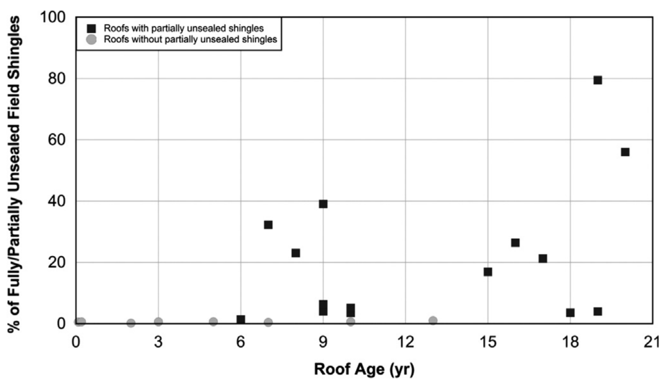

Fig. 6. Percent of unsealed shingle strips located in the field of the roof verses roof age—Florida shingles. (Fully and partially unsealed shingles combined).

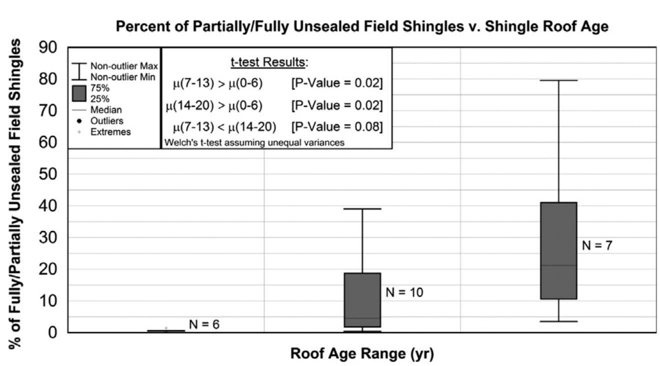

Fig. 7. Boxplot of unsealed shingle strips located in the field of the roof verses roof age at the time of investigation—Florida shingles.

3.3.2. Ridge and hip shingles

Twenty of the 27 surveyed roofs had partially and fully unsealed ridge and hip shingles. Unsealing occurred at the down-slope edges of hip and ridge shingles. Full adhesion was observed elsewhere. Two findings indicate that these unsealed shingles never properly sealed. First, in contrast to field shingles, the unsealed strip on hip and ridge shingles did not transfer sealant from the top surface of the sealant strip to the bottom surface of top shingle (Fig. 9), which is consistent with post-hurricane damage observations in FEMA (2005a). Second, the percentage of unsealed ridge and hip shingles shows no observable trend with age (Fig. 10).

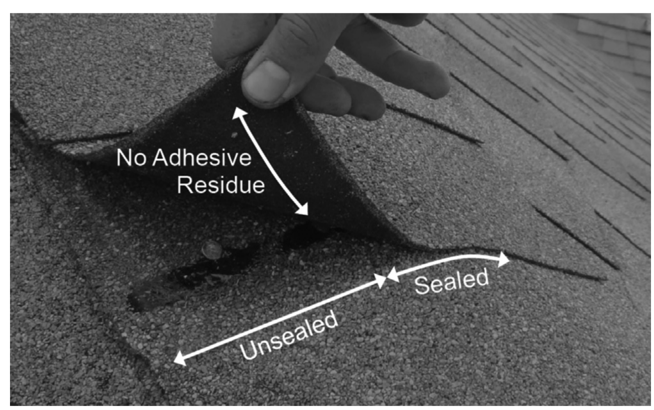

Fig. 9. Typical condition for partially unsealed ridge and hip shingle with an adhesive failure mode between the top shingle and sealant strip indicated by the lack of sealant residue on the underside of the shingle.

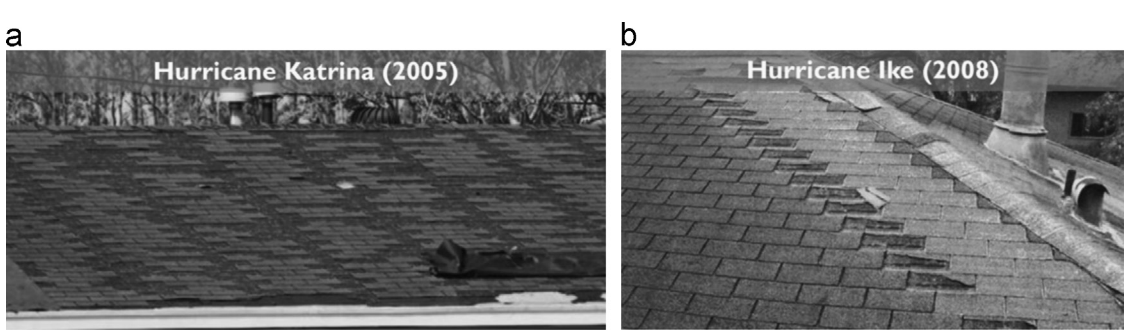

Fig. 8. Blown off three-tab asphalt shingles from (a) Hurricane Katrina in 2005 and (b) Hurricane Ike in 2008. [Photo (a) FEMA and Photo (b) John Minor].

The method of installation likely resulted in unsealed ridge and hip shingles. Ridge and hip shingles can be purchased either pre-manufactured or cut from three-tab shingles. Both pre-manufactured and cut three-tabs are originally flat shingle strips that are folded over the ridge and hip roof line and nailed to the substrate with two fasteners per shingle. Once folded, the edges of a ridge and hip shingle will tend to lift to reorient the shingle back to its original geometry. If the sealant strip is unable to bond the edge of the shingle at the onset of service, the shingle edge is not restrained from rising and may remain that way throughout its life expectancy–leaving it partially unsealed at its edges and sealed along its centerline where the crease in the shingle is formed.

4. Study 2: Full-scale testing of asphalt shingle roof systems

Seventeen full-scale 6:12 slope roofs covered with ASTM D7158 Class H asphalt shingles were subjected to fluctuating winds at the IBHS Research Center in Richburg, SC. The shingle roofs were installed by licensed roofing contractors during the summer of 2011 and conditioned outdoors for 11 months. Using the same method outlined in Section 3.1, surveys were performed on each roof specimen just prior to wind testing. The surveys found fully and partially unsealed field shingles on eight of the 17 roof specimens and partially unsealed hip shingles on all hip roofs, which was of greater frequency than the field surveys. This paper focuses on the wind performance differences between the sealed and unsealed field and hip shingles to assess the vulnerability of pre-existing unsealed shingles to strong wind.

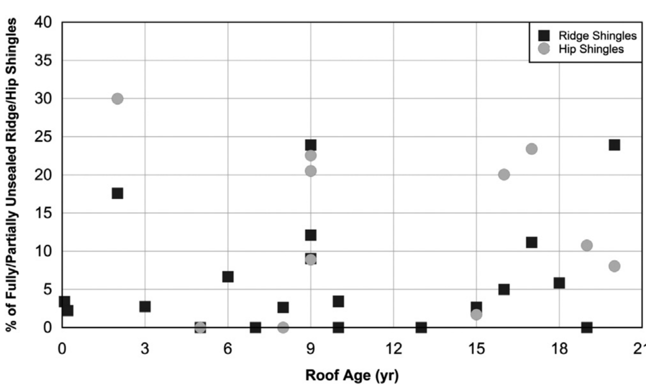

Fig. 10. Percent of fully and partially unsealed hip and ridge shingles verses roof age. Two roofs contained hip and ridge shingles without sealant strips and are not shown in figure.

4.1. Experimental design

The test matrix consisted of two laminate shingle products and one three-tab product; all classified as ASTM D7158 Class H and ASTM D3161 Class F wind resistant shingles. A licensed roofing contractor installed the asphalt shingle roof systems in conformance to the 2010 Florida Residential Building Code Section R905.2 and manufacturers' guidelines. Shingle fasteners were pneumatically driven 12 ga electroplate galvanized nails with a 9.5 mm (3/8 in.) diameter head and 31 mm (1.25 in.) shaft length. Three-tab shingles were secured with four nails per strip, while laminates were secured with six nails per strip. The roof specimens were placed on a base structure (9.1 m W $\times$ 12.2 m L $\times$ 2.4 m H) with a permanent half-roof on one end to form an enclosed test structure (Fig. 11).

Once installed on the test structure, field, hip, and ridge shingles were surveyed following the procedure described in Section 3.1. Painters tape was placed on all shingles containing an unsealed length greater than 51 mm (2 in.), and overall photographs of each roof slope were captured to document the location of unsealed shingles. While the wind test sequence detailed in Section 4.1.1 was ongoing, seven high-definition video cameras recorded the performance of the roof cover. Following the test, the roof cover was inspected for surface cracking, material tears, pull-through at fastener heads, shingle blow off, and damage to the edge fastening. Field notes, roof plans, and photographs were used as part of the documentation process.

4.1.1. Wind test sequence and boundary layer simulation

The full-scale test facility at the IBHS Research Center is designed to replicate turbulent boundary layer flows at a sufficient scale to evaluate the performance of a single-family home. Wind is generated by 105 vaneaxial fans grouped into 15 subarrays under individual fan speed control. Wind speed records are derived from the Davenport (1961) spectrum accounting for desired mean velocity, peak velocity, terrain exposure, and turbulence characteristics (Liu et al., 2011). Five records were created for the shingle roof tests: four sequences of 30 min each with fluctuating wind replicating the turbulent boundary layer (henceforth, Wind Levels 1a, 1b, 2, and 3), corresponding to 3-s open exposure gust winds in the ASCE 7 wind load provisions. The fifth record was a 17-min sequence corresponding to a series of step-and-hold wind velocities up to the maximum wind speed capacity of the facility (henceforth, Wind Level 4). The first three test roofs were subjected sequentially to Wind Levels 1a, 2, and 3, while the remaining 14 roofs were subjected sequentially to Wind Levels 1b, 2, 3, and 4.

Table 2 list the measured mean/peak velocities and longitudinal/lateral turbulence intensities of the five test sequences. Wind data were captured using a Turbulent Flow Instruments Cobra

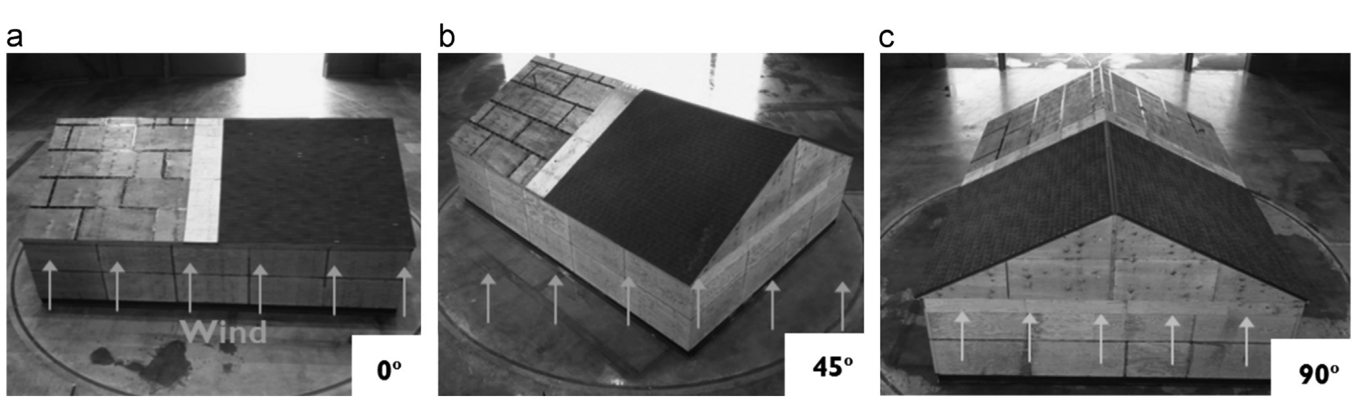

Fig. 11. Wind directions for gable and hip roof specimens.

Table 2
Wind test sequence duration, wind speeds, and turbulence intensities.

Wind level	Test duration (min)	Mean wind speed[a] (m/s) [mph]	Peak instantaneous wind speed[a,b] (m/s) [mph]	Longitudinal turbulence intensity (%)[a]	Lateral turbulence intensity (%)[a]
1a	30	18 [40]	33 [74]	23	9
1b	30	23 [51]	44 [98]	23	9
2	30	28 [63]	45 [100]	23	9
3	30	28 [63]	54 [120]	23	9
4	1	41 [92]	–	14	6
	5	48 [107]	–	14	6
	5	50 [112]	–	14	6
	5	54 [120]	–	14	6

[a] Measured at 5 m (16 ft) with velocity sampled at 500 Hz.
[b] Wind speeds varied approximately ±1 m/s (2 mph) per day due to air density fluctuations.

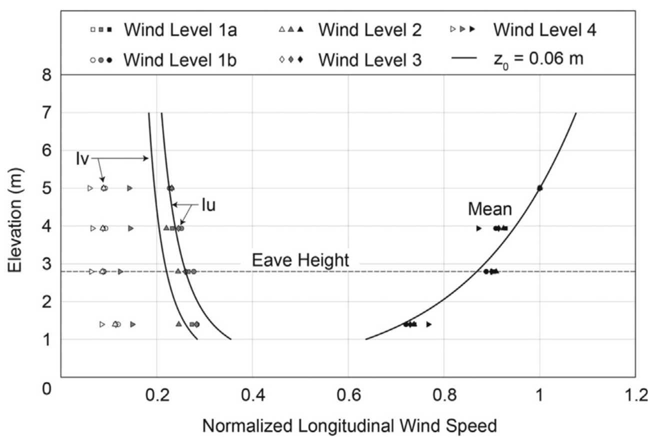

Fig. 12. Measured and best fit theoretical normalized mean velocity, longitudinal turbulence intensity, and lateral turbulence intensity.

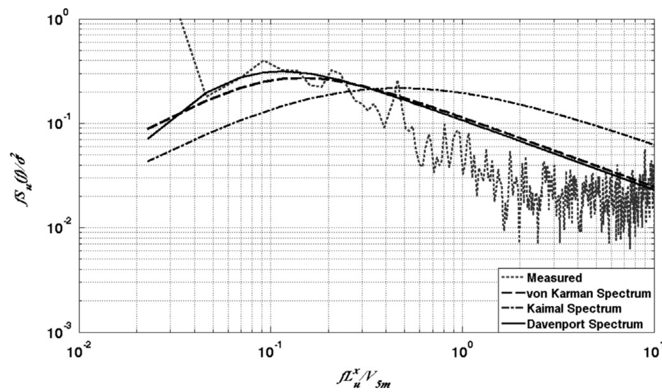

Fig. 13. Normalized wind spectrum of Wind Level 3 (measured at 5 m) with comparison to von Karman (1948), Kaimal et al. (1972), and Davenport (1961) spectra.

Probe three-axis velocity sensor mounted at a location 0.3 m upwind of the windward face of the test structure (without the test structure in place) on the centerline of the fan opening at a height of 5 m (16.4 ft) above the chamber floor. Additional measurements of velocity were made at heights of 1.4 m (4.6 ft), 2.8 m (9.2 ft), and 3.9 m (12.8 ft) to produce the normalized mean wind velocity, lateral turbulence intensity, and longitudinal turbulence intensity vertical profiles shown in Fig. 12. Theoretical mean velocity profiles were generated from Engineering Science Data Unit (ESDU) (1983) and normalized to 5 m. Theoretical longitudinal (I_u) and lateral (I_v) turbulence intensity profiles were generated from Engineering Science Data Unit (ESDU) (1983), assuming that ($s/u_*=2.5$) for I_u and ($s/u_*=2.2$) for I_v. The theoretical profiles shown in Fig. 12 correspond to the best-fit roughness length ($z_0=0.06$ m). Fig. 13 shows the normalized longitudinal wind spectrum measured at 5 m (16.4 ft) during the highest wind speed level (3). Comparisons to von Karman (1948), Kaimal et al. (1972), and Davenport (1961) model spectra are also shown. Reasonable agreement between the data and model was found except for the lateral turbulence intensity, which was attributed to the limited range (∼30 degrees) of the rotational vanes.

4.2. Results

4.2.1. Pre-wind test unsealed shingle surveys

The percentage of pre-wind test unsealed shingles ranged from 0% (nine of 17 roof specimens) to 12% (one three-tab roof specimen). Unsealed shingles on the laminate roofs exhibited adhesive failures between the sealant strip and overlapping shingle, whereas unsealed three-tab shingles most frequently failed cohesively within the sealant strip. The location and length of unsealing on the partially unsealed shingles was more random than those observed in the roof surveys described in Section 3. Partially unsealed hip shingles were found on all hip roof specimens prior to wind testing. The location of the hip shingle's partial unsealing (edge) and failure mode (adhesive) was the same as that observed for the partially unsealed hip shingles in the in situ roof surveys (Section 3). It is not known if moving the roof samples from outdoors to the test chamber caused some shingles to unseal, although significant care was taken in transport to minimize this potential.

4.2.2. Wind performance of shingles installed in the field of the roof

Visible wind-induced shingle damage included surface cracking, pull-through of shingles over fasteners, and blow off. Damage initiated either from shingles identified as unsealed prior to wind testing – the focus of this paper – or pull-through of eave or rake roof edge shingles over edge fasteners. The percentage of damaged roof area on the 12 laminate roofs ranged from 0 to 2.5%, whereas the range on the five three-tab roofs was 1–55%. The laminate roofs sustained less damage than the three-tab roofs due to: (1) lower quantity of pre-wind partially/fully unsealed shingles and (2) better resistance to progressive lifting, where three-tab eave and rake shingles suffered fastener head pull-through.

One example of the consequence of pre-wind test unsealed shingles is given for a three-tab shingle hip roof specimen at the 45° wind orientation (Figs. 14 and 15), selected because of its relatively high percentage of pre-wind test unsealed shingles. Roofs with lower quantities of pre-wind test unsealed shingles exhibited similar statistics on sealed shingle damage relative to the

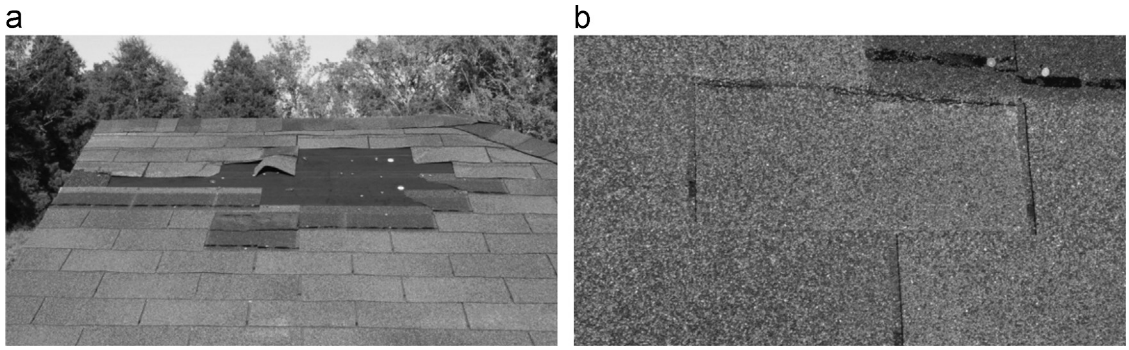

Fig. 14. (a) Blow off of shingles initiated by pre-wind test unsealed shingles. (b) Horizontal crack formed by lifting of the unsealed tab during wind testing.

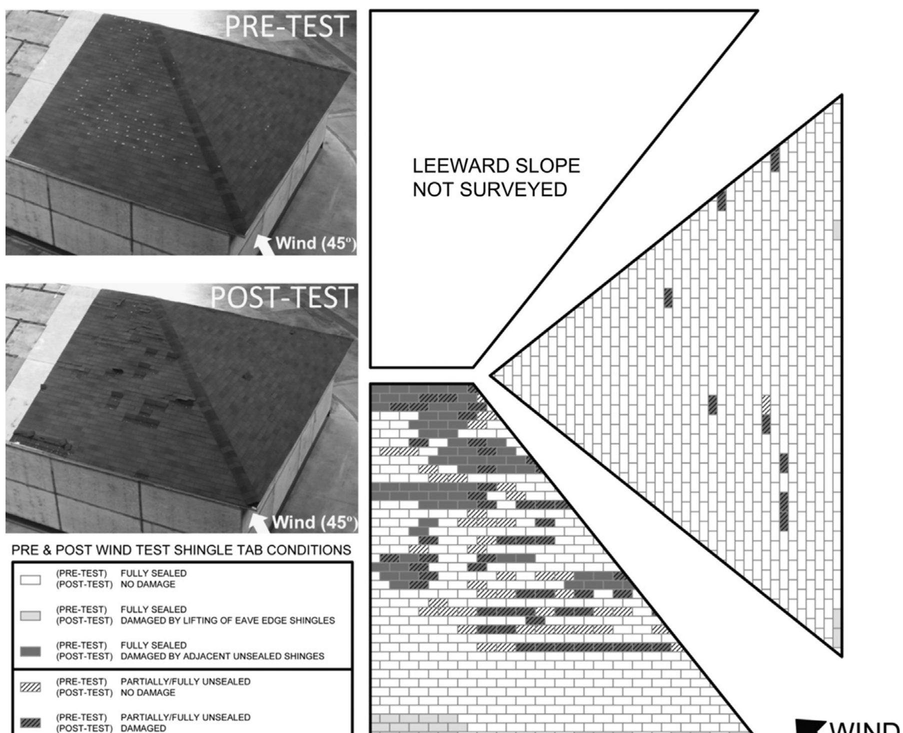

Fig. 15. Hip roof three-tab shingle specimen pre- and post-test conditions with pre-wind test unsealed shingles denoted by tape in the top left photo and the post-test condition summarized in the roof plan at right.

number of unsealed shingles. The pre-wind test roof survey of the hip roof specimen shown in Fig. 15 found fully or partially unsealed shingle tabs on 9% of the tabs located on the windward roof slopes.

Post-test analysis of the high-definition video captured during the wind tests showed the progression of damage. Beginning in Wind Level 1b, several fully unsealed shingle tabs lifted with larger "sheeting" type lifting and blow off occurring near the ridge where unsealed shingles were adjacent to one another (Fig. 14—same roof as shown in Fig. 15). Additional shingle tabs lifted throughout Wind Levels 2–4 due to their pre-existing unsealing, causing damage to adjacent fully sealed shingles.

A second analysis of the wind test footage was conducted to define the damage outcome of all shingle tabs located on the windward roof slopes. Each shingle tab was assigned a color and hatch pattern representing its pre-wind test sealed or unsealed condition and post-wind test damage outcome. The results of this analysis are shown in Fig. 15. A statistical comparison of the number of damaged shingles to pre-wind test shingle tab condition is shown in Fig. 16. Approximately 13% of the windward shingle tabs (147 tabs out of 1102) sustained some form of damage (e.g., blow off or surface cracking)—8% occurred on shingles identified pre-test as fully sealed and the remaining 5.5% occurred on shingles identified pre-wind as partially/fully unsealed (Fig. 16a). Thus, nearly 60% of the pre-wind unsealed tabs sustained some form of wind damage. Whereas, only 9% of the pre-wind test sealed tabs sustained wind damage, all of which were initiated by either adjacent unsealed shingles or shingles that lifted at the eave.

In summary, the results of this limited study indicate that wind damage initiates from partially unsealed shingles and lifting of shingles on the edge of the roof (Fig. 16b). Shingles that were fully sealed prior to wind tests did not exhibit damage during wind testing. It is therefore concluded pre-existing unsealed shingles in the field of the roof dramatically increase the roof's overall wind damage vulnerability.

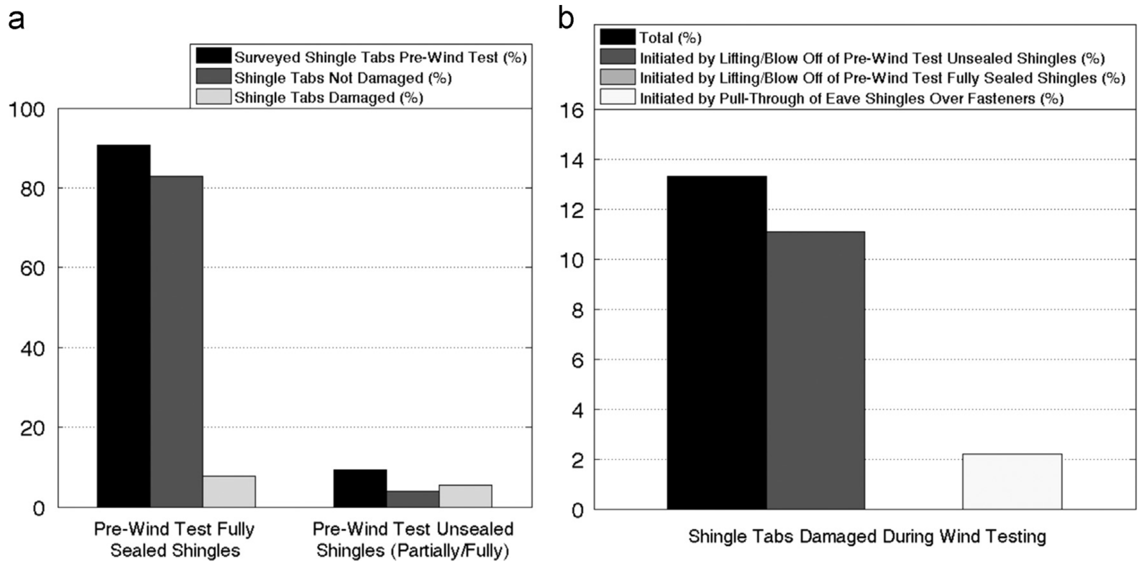

Fig. 16. Statistical comparisons for the roof specimen shown in Fig. 15 (a) Comparison of the post-wind test condition of windward shingle tabs stratified by pre-wind test sealed/unsealed condition. (b) Contribution of each potential initiator of shingle wind damage on the overall damage rate.

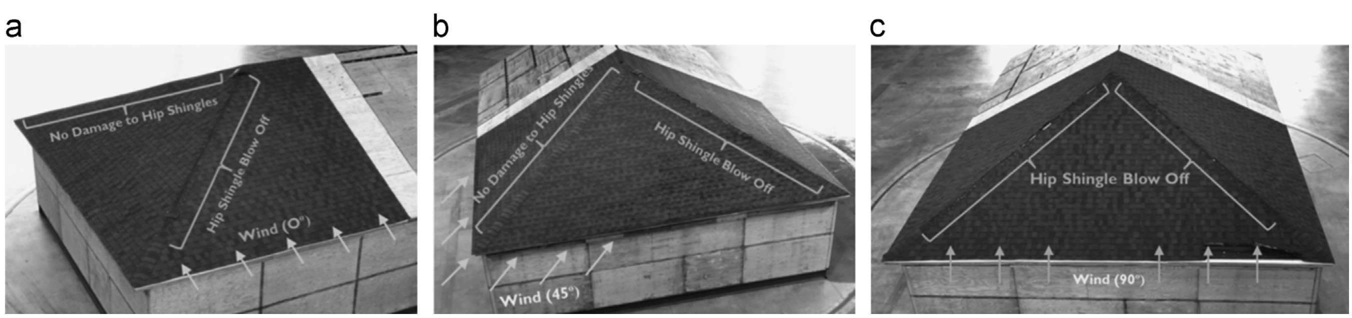

Fig. 17. Characteristic hip shingle blow off patterns: (a) 0°, (b) 45°, and (c) 90° wind directions.

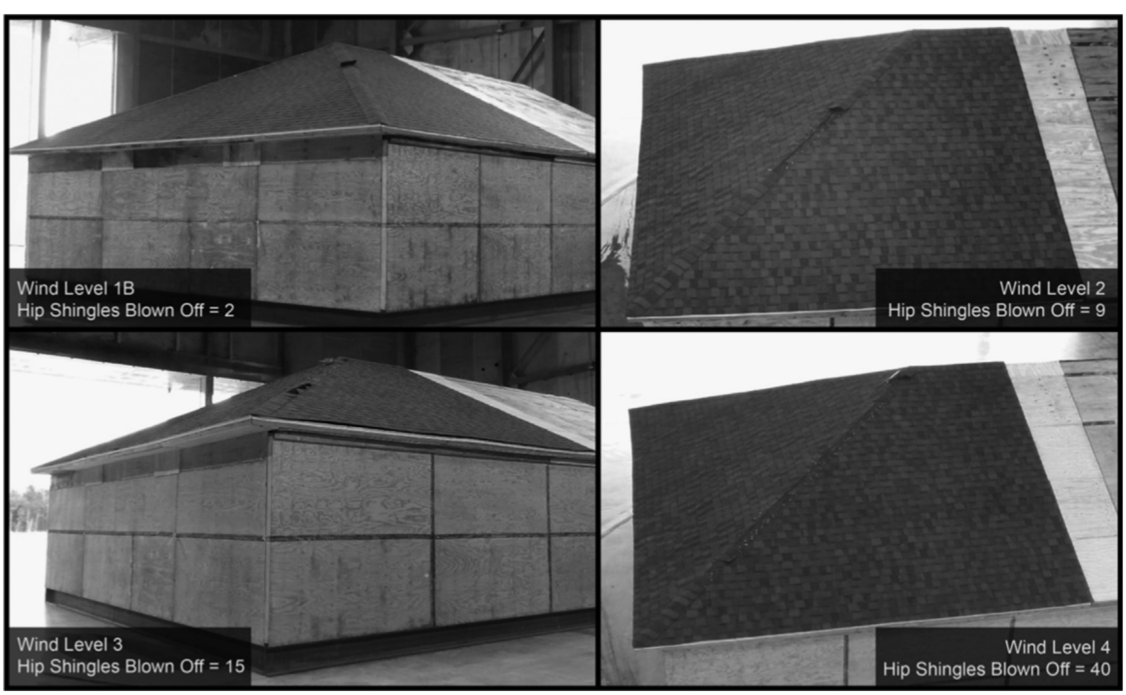

Fig. 18. Progression of hip shingle blow off through the wind test sequence for specimen oriented at the 0° wind direction. This was a typical observation among all hip roof specimens tested.

4.2.3. Hip shingle wind performance

Hip shingles blew off of all hip roof specimens. The quantity of blown off hip shingles ranged from 41% to 86% of the total number of hip shingles installed on the roof. Wind flow roughly parallel to the leading edge of the hip shingles produced the largest hip shingle loss (Fig. 17). Loss of pre-wind unsealed hip shingles initiated damage to sealed hip shingles upslope, as described below.

One example of the progression of hip shingle blow off is given in Fig. 18. For this specimen oriented at the 0° wind direction (see Fig. 11), the first loss of hip shingles occurred during Wind Level 1 with the blow off of two shingles (Fig. 18a). The first shingle to lift was identified prior to the wind test as partially unsealed on its windward edge, and blow off occurred after the lifted shingle pulled through the fastener head. Blow off then progressed upwards during Wind Levels 2 and 3 on shingles that were previously adhered directly upslope from the initially blown off shingle (Fig. 18b and Fig. 18c). A pre-wind partially unsealed hip shingle also blew off towards the bottom of the roof during Wind Level 3 causing progressive blow off through Wind Level 4 (Fig. 18d). By the end of the wind test, only 10 out of the 50 hip shingles on the windward hip line remained on the roof. Damage vulnerability is, therefore, magnified for hip shingles that are unsealed on their windward edges, and loss of unsealed shingles instigates progressive failure of upwind adjacent sealed hip shingles.

5. Conclusions

The results of two studies demonstrate that asphalt shingles are prone to not sealing or unsealing over time, and this condition increases their vulnerability in strong winds. Thirty roofs in Florida and Texas were surveyed for unsealed shingles. All roofs contained unsealed shingles with occurrence of unsealing reaching up to 86% of the total amount of installed shingles. The quantity of unsealed shingles installed in the field of the roof generally increased with roof age, whereas the quantity of unsealed hip and ridge shingles showed no discernible relationship to roof age.

When unsealed shingles were observed in the field of the roof, more than 99% of them were unsealed along a partial length of their sealant strip line. The plane of fracture where unsealing occurred – cohesively in the sealant strip – and location of unsealing was consistent in the partially unsealed shingles, indicating a systematic failure of the sealant strip to remain adhered. The specific cause is unknown, but the observed increase in the total amount of unsealed field shingles with a roof's in-service age indicates that the effects of natural aging (Berdahl et al., 2008) influence the partial unsealing of field shingles. Blow off patterns of shingle roofs in previous hurricanes were similar to the spatial patterns that result from partially unsealed field shingles, and experimental results from the wind tests performed at the IBHS Research Center demonstrate that the wind vulnerability of partially unsealed field shingles is greater than that of sealed shingles. Further work remains to identify the specific mechanism (s) that cause unsealing. Future research should also address the effect of climate on the occurrence of partially unsealed shingles, and the contribution of partially unsealed shingles to shingle wind damage observed in regions outside of the southeast United States. This knowledge is critical for the development of appropriate retrofit guidelines for existing shingle roofs and for future asphalt shingle design, manufacturing, and installation.

For hip and ridge shingles, the installation technique combined with improperly placed nails in the sealant strip line are the most likely factors causing partial unsealing at the edge of the shingle. In the wind tests at the IBHS Research Center, blow off of hip shingles initiated from the lifting of pre-existing partially unsealed hip shingles, then progressed up the roof slope. Retrofit solutions to seal the edges of hip and ridge shingles are available in FEMA (2012), but further work is necessary to quantify the long-term durability and increased wind performance of the proposed retrofit.

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